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Feasibility study of a high-performance $LaBr_3(Ce)$ calorimeter for future lepton flavor violation experiments

A. Papa[a,*], M. De Gerone[b], S. Dussoni[c], L. Galli[a,c], D. Nicolò[c,d], G. Signorelli[c]

[a] *Paul Scherrer Institut PSI, CH-5232 Villigen, Switzerland*
[b] *INFN Sezione di Genova, Largo Dodecaneso 33 , 16146 Italy*
[c] *INFN Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy*
[d] *Dipartimento di Fisica dell'Università degli studi di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy*

Abstract

$LaBr_3(Ce)$ is a very attractive material due to its ultra high light output and its fast response, resulting in a good candidate as a crystal for a calorimeter able to provide simultaneously very high energy and timing performances. We report here a first test with a cylindrical 3" × 3" $LaBr_3(Ce)$ crystal coupled to PMT (Photonics XP53A2B), where we explore the detector performances at relative high energies, on the region of interest for future charged Lepton Flavor Violation (cLFV) experiments, using photons in the interval of 55÷83 MeV from π^0 decays up to 129 MeV from the radiative capture of negative pions on protons.

Keywords: $LaBr_3(Ce)$ crystals, calorimeter, timing measurements

1. Introduction

Charged Lepton Flavor Violation (cLFV) can reveal the structure of new physics up to the energy scale of 10^3 TeV, i.e. well outside the LHC searches reach. The observation of cLFV phenomena such as $\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ conversion relies on development of detector performance in terms of energy, time and position resolution for gamma rays and positrons or electrons in the energy range 10 ÷ 100 MeV ([1], [2], [3], [4]).

$LaBr_3(Ce)$ is a very attractive candidate as a detector medium ([6], [7], [8]) for the energy range of interest in cLFV searches, thanks to its ultra high light yield (LY), fast emission, possibility of internal energy scale monitoring by means of intrinsic La radioactivity. These properties together with its high density, result in a good candidate as a crystal for a compact calorimeter able to provide simultaneously very high energy and timing performances. Tab. 1 summarizes the main scintillation properties compared to other widely used scintillators, where a Figure of Merit (F.o.M.) is defined for a quick comparison, as the ratio of the product of the light output and the density versus the scintillation decay time.

In our previous work a timing resolution of ≈ 85 ± 10 ps at 11.6 MeV was obtained as a first timing measurement at relative high energy [9]. In this work we exposed for the first time the biggest, although relative small, available 3" × 3" $LaBr_3(Ce)$ crystal at high energy photons (55 ÷ 83 MeV and 129 MeV) as a first step of dedicated studies planned in the next future.

2. Experimental set-up

Negative pions with a momentum of 70.5 MeV/c are stopped in a liquid hydrogen (LH_2) target (diam. 50 mm, length 75 mm). The charge exchange reaction and the radiative capture

$$\pi^- + p \to \quad \pi^0 + n \quad (Charge\ exchange) \qquad (1)$$

*Corresponding author
Email address: angela.papa@psi.ch (A. Papa)

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Table 1: Main scintillation properties for widely scintillator media. A F.o.M. is given as defined into the text.

Scintillator	Density $\rho(\mathrm{g/cm^3})$	Light Yield LY(ph/keV)	Decay time τ (ns)	F.o.M. $\sqrt{(\rho \cdot \mathrm{LY})/\tau}$
$LaBr_3$(Ce)	5.08	63	16	4.55
BC404	1.03	12	1.8	2.63
LYSO	7.1	27	41	2.17
YAP	5.35	22	26	2.13
LXe	2.89	40	45	1.61
NaI(Tl)	3.67	38	250	0.75
BGO	7.13	9	300	0.46

$$\hookrightarrow \gamma\gamma \qquad (2)$$

$$\pi^- + p \rightarrow \quad \gamma + n \quad (Radiative\ Capture) \qquad (3)$$

are the two competitive processes detected with our experimental set-up. The two (Top and Bottom) plastic scintillators ($4 \times 4 \times 4$ cm^3) BC404 coupled to very fast Hamamatsu R5924 PMTs and the single 3" $\times$ 3" $LaBr_3$(Ce) crystal coupled to a Photonics XP53A2B PMT were mounted as shown in Fig. 1, in order to select the back-to-back γ's from the π^0 decay and n-γ from the π^- radiative capture. A waveform analysis was performed using the DRS4 evaluation board as a fast digitizer [10] (4 channels, 11.5 bit, 0.7-5 Gsamples/s, max band width: 700 MHz). External NIM modules provided the trigger logic, supplies etc.

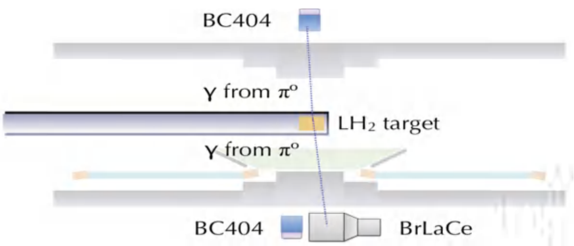

Figure 1: Test setup (side view). The π^- are stopped into the LH_2 target and back-to-back events can be detected by the Top BC404 detector and the Bottom $LaBr_3$(Ce) detector.

3. Results

Fig. 2 shows the observed time structure for selected back-to-back events with the $LaBr_3$(Ce) crystal (from now BrLaCe) and the Top plastic BC404. The used variable is the time difference between the two detectors, $\Delta T = T_{BrLaCe} - T_{BC404}$. We can recognize three well-defined region: a central peak ($\Delta T \approx 0$, blue) associated with the charge exchange (the two γ's arriving simultaneously on both detectors) and two lateral

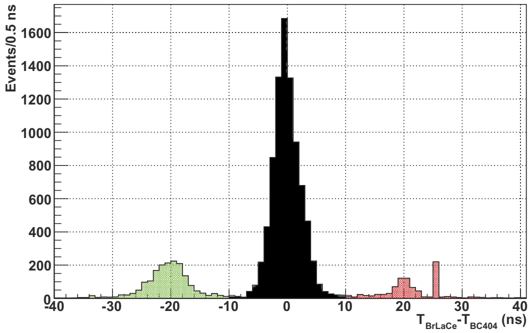

Figure 2: Time structure for back-to-back events selected with the $LaBr_3$(Ce) crystal and the Top BC404.

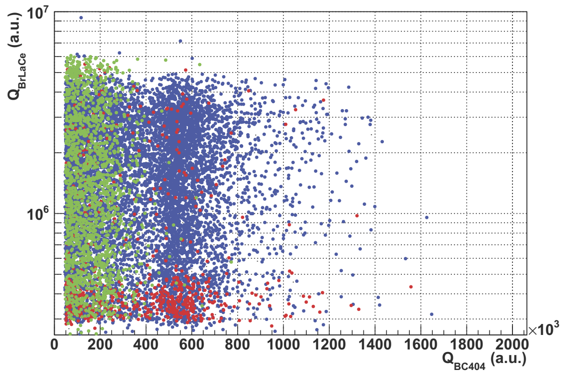

Figure 3: The collected charge on the $LaBr_3$(Ce) detector versus the BC404 detector selecting the three categories of events by means of timing cut: γ in the $55 \div 83$ MeV energy interval ($|\Delta T| < 10$ ns, blue), γ at an energy of 129 MeV and neutrons at 9 MeV, with n into the $LaBr_3$(Ce) ($\Delta T > 10$ ns, red) and n into the BC404 ($\Delta T < -10$ ns, green).

peaks, related to the detection of the n-γ coincidence, which are displaced by ± 20 ns (green and red), accordingly with the kinematics of the radiative capture products and the setup geometry. The scatter plot of the BrLaCe charge versus the BC404 charge is shown in Fig. 3 where a time selection is used to identify the three categories of events. The collected charge on the BrLaCe detector is also given in Fig. 4. An energy calibration, valid in the low energy region where the non-linear effects due to the small dimension of the crystal are negligible, was performed by means of the 17.6 MeV γ-line from the $p + Li \rightarrow Be + \gamma$ nuclear reaction using a Cockcroft-Walton accelerator, and the 1.45 MeV La self-radioactivity line. The reconstructed energy is consistent with what we expect.

A simplified Monte-Carlo simulation was done, look-

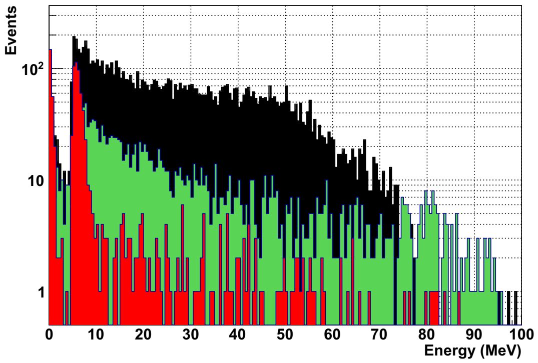

Figure 4: The collected charge on the $LaBr_3$(Ce) detector for the three categories of events: γ in the $55 \div 83$ MeV energy interval (blue), γ at an energy of 129 MeV (green) and neutrons at 9 MeV (red).

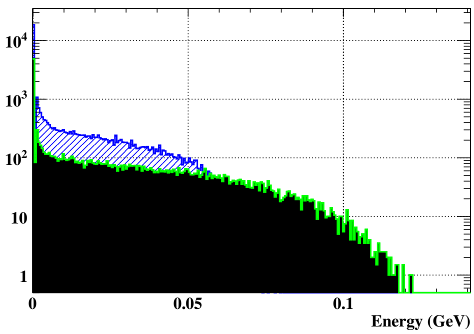

Figure 5: Monte Carlo simulation. Energy loss in the $3'' \times 3''$ $LaBr_3$(Ce) for γ in the $55 \div 83$ MeV energy interval (blue) and at an energy of 129 MeV (green).

ing at the energy loss for high energy γ-ray in the present detector (see Fig. 5), showing a nice agreement with the data, and the containment as a function of energy for future developments. A detector length of 30 cm addresses an almost full energy containment up to 129 MeV, which for instance could be compared with the MEG calorimeter whose thickness was set to 60 cm.

4. Prospects and Conclusion

A next test is planned to refine the present result and to investigate in depth the response linearity ([11], [12]). With a longer time scale, we are studying a different geometry for a prototype of calorimeter consisting of a 4×4 array made with smaller crystals i.e.$1.5 \times 1.5 \times 8$ inch which should contain at least 95% of the shower energy, with some additional advantages over a single larger crystal: (1) the energy deposit on each crystal is lower, resulting in a better control of linearity; (2) the intrinsic radioactivity can be exploited to have a continuous monitoring system; (3) the event reconstruction can be performed with higher accuracy by a segmented detector; (4) the smaller crystals are cheaper because of their easier production process. Also, we are going to study the possibility of using Silicon PhotoMultipliers to read out the scintillation light, which can result in further performance improvement (especially of time resolution) as well as in a simpler implementation of such a detector in the presence of a magnetic field (e.g. in case of a magnetic spectrometer for charged particle tracking/momentum selection).

$LaBr_3$(Ce) is a relative recent scintillator which offers the highest light output together with a very fast time response leading to a strong candidate for future cLFV search. The small crystal size is a present limit on the investigation of the full characteristics of this kind of medium in the field of the high energy physics.

Acknowledgments

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